# Photovoltaically powered modulating retroreflectors

**R. J. Walters**
**J. L. Murphy**
**W. S. Rabinovich**
**G. C. Gilbreath,** MEMBER SPIE
United States Naval Research Laboratory
4555 Overlook Avenue
Washington, D.C. 20375
E-mail: Robert.Walters@NRL.NAVY.MIL

**D. M. Wilt**
NASA Glenn Research Center
Cleveland, Ohio 44135

**M. A. Smith**
Ohio Aerospace Institute
Cleveland, Ohio 44135

**M. J. Krasowski**
NASA Glenn Research Center
Cleveland, Ohio 44135

**P. P. Jenkins**
**D. Scheiman**
Ohio Aerospace Institute
Cleveland, Ohio 44135

**J. H. Warner**
United States Naval Research Laboratory
4555 Overlook Avenue
Washington, D.C. 20375

**S. R. Messenger**
SFA Inc.
Largo, Maryland 20774

**J. R. Lorentzen**
Ohio Aerospace Institute
Cleveland, Ohio 44135

**G. P. Summers**
United States Naval Research Laboratory
4555 Overlook Avenue
Washington, D.C. 20375

**Abstract.** The development of a photovoltaically (PV) powered laser communication system that constitutes a miniature, highly energy-efficient wireless communication technology is described. The technology is based on the direct integration of a multiquantum well (MQW) modulating retroreflector (MRR) optical communication node and a monolithically integrated module (MIM) PV power source. The MQW MRR optical data link exploits the shift in the MQW absorption peak under an applied reverse bias to modulate incident laser light, enabling binary encoding of data for transfer. A MIM consists of many individual solar cells monolithically integrated on a single substrate and offers the design versatility necessary to enable efficient electrical conversion of both incident sunlight and the system laser light and the ability to match the voltage output to the MRR requirements. A description of the development of the MRR and MIM components of the system is given. Results of bench-top demonstrations of the operational system are presented.
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Subject terms: photovoltaics; quantum well modulator; optical data link.

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## 1 Introduction

This paper presents the design and implementation of a photovoltaically powered optical data link. The work is being performed under funding from the National Aeronautics and Space Administration (NASA) Space Communications Project, and the goal of the research is to produce a miniature, self-powered sensor system with communication capabilities that can operate autonomously for extended time periods in extreme environments such as the Martian surface. The current effort is focused on (1) developing the photovoltaic (PV) power source specifically engineered to power the sensor payload and the optical data link and (2) developing the optical data link. The sensor payload is en-

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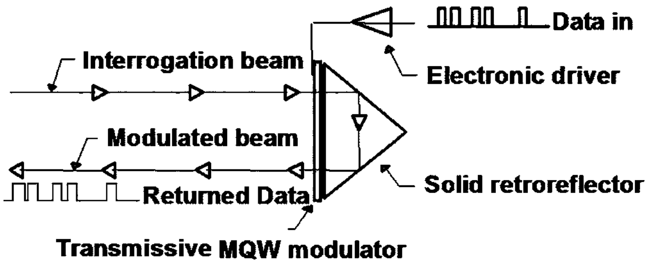


**Fig. 1** Schematic diagram of a MQW MRR.

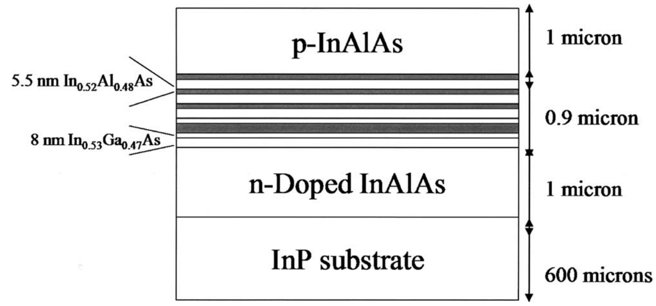


**Fig. 3** Schematic cross section of the MRR device operating at 1550 nm developed by NRL.

visioned to be something like a low-power camera, a temperature sensor, or an accelerometer, and an existing sensor technology will be used in the system. The target parameters for the final system are 50 mW of power transmitting data at 100 kHz at a duty cycle of 30 min within a package approximately $2\times 2$ cm by 0.5 cm thick.

## 2 Modulating Retroreflectors

A modulating retroreflector (MRR) consists of a multiple-quantum-well (MQW) optical detector mounted in front of a retroreflector[1] (http://mrr.nrl.navy.mil). A MQW MRR data link is shown schematically in Fig. 1. The MRR is driven by an analog or digital signal from an electronic driver within the system (in the present system, the onboard sensor), which is impedance-matched to the MQW detector. The system exploits the shift in the absorption peak of the MQW under an applied reverse bias (Fig. 2) so that an interrogation laser beam is either passed or blocked by the MQW. In this way, the ac-driven MQW detector modulates the reflected light, enabling binary encoding of the data to be transferred. The device itself can support up to 12 Mbits/s at about 100 mW. In the present application, the data rate is reduced to reduce the power requirements. The communications terminal on the payload consists only of the MQW MRR, drive electronics, and sensor, and can be of the order of 10 g or less per unit.

The wavelength for optical communication within the MQW MRR system is defined by the quantum well structure. The Naval Research Laboratory (NRL) has fielded systems operating at 980 nm using MQWs based in the GaAs material system.[2] For the presented research, MQW MRR devices operating at 1550 nm are being developed for eye safety and to leverage advances in lasers and optical advances at this wavelength. The internal structure of the first-generation 1550-nm MQW MRR is shown in Fig. 3. This structure results in a square-well potential, as shown schematically in Fig. 4. Photon absorption occurs by the creation of an electron-hole pair (exciton) within the MQW region. The absorption wavelength is defined by the exciton energy, which is controlled by the valence-conduction band edge. The bending of the valence and conduction bands by an applied bias causes a shift in the exciton energy and, thus, the absorption energy. This is a well-known phenomenon referred to as the quantum Stark effect.[3] It is by this mechanism that the MRR is used as an electro-optic shutter where data is fed into the MRR in the form of a time-varying voltage pulse that induces oscillations in the absorption wavelength, which, in turns impresses the data onto the returned laser signal.

The strength of the MRR signal can be measured in terms of the contrast ratio, which is the ratio of the return laser power with applied bias to that without a bias applied to the MQW detector. An example of the contrast ratio measured as a function of wavelength for the square well modulator is shown in Fig. 5, and it can be seen that contrasts as high as 2 can be achieved. However, the effect of the applied bias on the electron bands is relatively weak, so voltages of 15 V or more are required to achieve these contrast ratios, which can be difficult to achieve in a low-power application.

To reduce the MRR operating voltage, and hence power requirements, coupled-well structures have been developed.

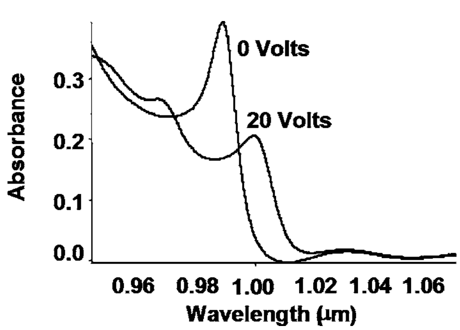


**Fig. 2** Example of the shift in absorption peak of a MQW under applied reverse bias.

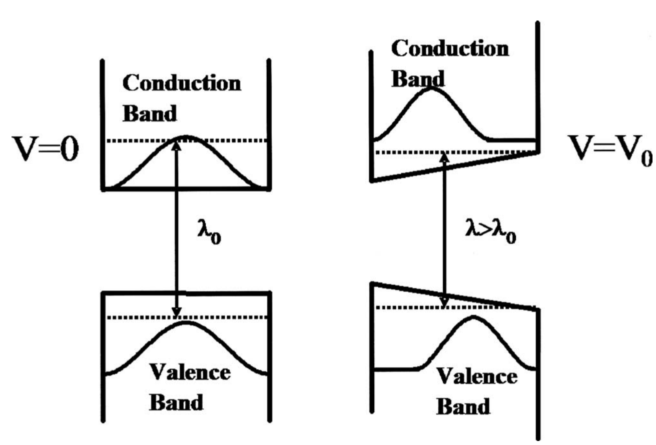


**Fig. 4** Schematic representation of the square-well potential created within the MQW of Fig. 3.

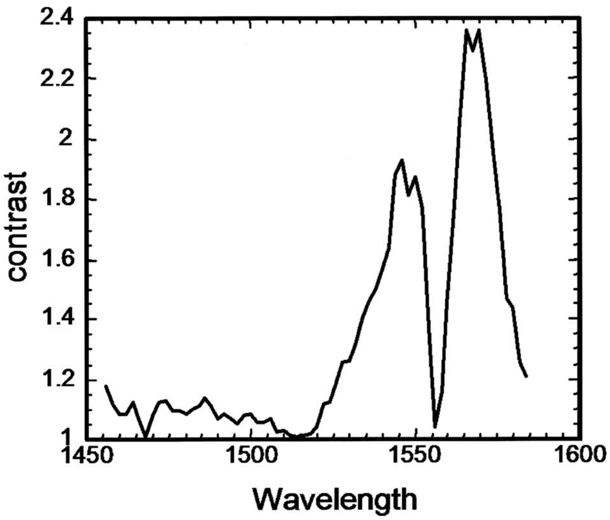


**Fig. 5** Contrast ratio data measured from a 1550-nm MRR operating voltage of 15 V.

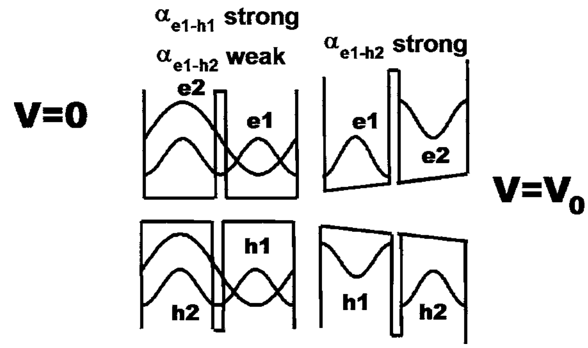


**Fig. 7** Schematic diagram of the band structure within a coupled well.

A coupled well is a quantum well that places two different quantum well structures in contact with each other. A schematic drawing of such a coupled-well structure is shown in Fig. 6. The $In_{0.58}Ga_{0.42}As$ layer is the well material. The $In_{0.47}Al_{0.53}As$ layers are the barriers where the different thicknesses give rise to the coupled-well configuration. A schematic diagram of the band structure of the coupled-well system is shown in Fig. 7. In the absence of an applied bias, symmetric and asymmetric bands exist, which enable photon absorption. Application of a bias as low as 5 V splits this symmetry, thereby altering the absorption edge. As a result, contrast ratios over 2 can be achieved with the biases of only 5 V (Fig. 8).

Several of the coupled-well MRRs were grown, fabricated, and characterized. In particular, the optical modulation performance of the MQW modulator was examined to determine options for operating at voltages lower than 5 V. It was determined that a drive voltage of 4 rather than 5 V would sacrifice less than 1 dB of communication margin while reducing power consumption by about 2 dB. It has also been found that when considering both contrast ratio and transmission, an extended optical bandwidth for communication can be used. Efforts are now focused on determining the optimum operation conditions from a power and performance standpoint.

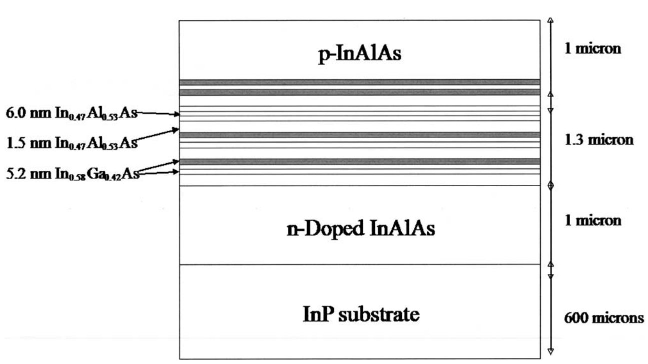


**Fig. 6** Schematic drawing of an MRR based on a coupled-well design.

## 3 Monolithically Integrated Module (MIM) Technology

The PV power source under development is based on the NASA Glenn Research Center (GRC) patented MIM technology[4] that has been developed for thermophotovoltaics (TPVs). A MIM consists of many individual solar cells series connected on a single substrate. An example of a 1- $\times$1-cm$^2$ MIM consisting of InGaAs solar cells grown on an InP substrate is shown[5] in Fig. 9. For this material system, bandgaps ranging from 0.74 to 0.55 eV have been achieved, which corresponds to cutoff wavelengths ranging from 1.6 to 2.2 $\mu$m. Series connecting the cells enables the output voltage to be increased. Output voltages over 6.5 V and currents over 2 mA/cm$^2$ have been produced by 0.75-eV bandgap material under simulated 1 sun AM0 (air mass zero) solar illumination. The MIM technology offers the design versatility necessary to enable efficient conversion of both incident sunlight and the system laser light.

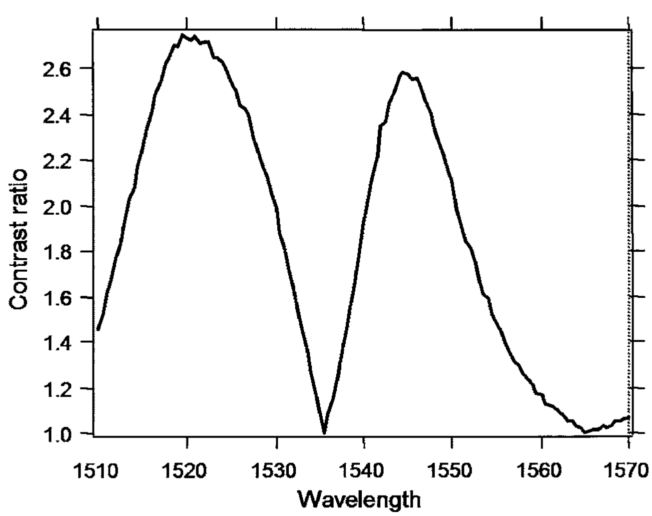


**Fig. 8** Contrast ratio values measured in a coupled-well MRR with an applied bias of 5 V.

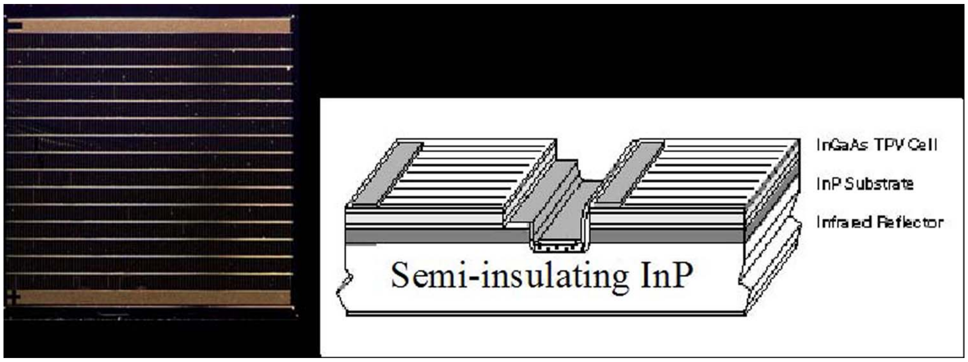


**Fig. 9** Photograph and schematic diagram of an InGaAs/InP MIM.

Furthermore, the MIM technology enables the design flexibility to match the PV output to the MQW MRR requirements.

In this project, the TPV MIM was redesigned for PV energy conversion assuming AM0 and 1550-nm laser illumination resulting in the internal device structure shown in Fig. 10. The overall structure of the MIM, i.e., the total number of individual cells within the MIM and the cell dimensions, was designed so that the device can deliver 10 mA at 5 V dc. The overall structure was also designed based on a 2-in.-diam InP wafer on which the structure will be grown. The wafer will have a center aperture to enable illumination of the MRR positioned behind the wafer. This design has been termed the "Power-Puck," and a schematic diagram is shown in Fig. 11.

A modeling exercise was performed to determine the optimum configuration for the MIM structure to meet these requirements. The current and voltage output of the MIM under AM0 illumination was calculated as a function of the number of individual cells in the MIM, and it was determined that an output of just over 7 mA at 5 V can be achieved from a MIM with 20 subcells that fills one quadrant of Power-Puck. Since there will be four such MIMs, the total current produced by the Power-Puck will be 4 times this amount. The modeling also showed that under laser illumination alone, at an incident power of $\sim$20 mW/cm$^2$, the required 5 V dc at a current of $\sim$2 mA can be achieved, and that the cell can maintain the required output voltage up to temperatures exceeding 70 °C.

A schematic diagram of the mask used to process the InP wafer for the Power-Puck is given in Fig. 12. Photographs of a prototype Power-Puck are shown in Fig. 13. The left-hand photograph is of the illuminated surface and shows a processed InP wafer. The right-hand photograph shows the nonilluminated side, where the MRR aperture is evident.

## 4 PV-Powered MRR Demonstrations

The initial demonstration of a PV-powered MRR data link consisted of an array of single-junction GaAs/Ge solar cells powering a GaAs-based, 980-nm MRR (Fig. 14) (Ref. 2). These are 2- $\times$ 2-cm$^2$ solar cells in the photograph. This system operated at 15 V and 2.5 kHz at a 12% duty cycle requiring about 50 mW of power. The graph in Fig. 14 shows the data transferred via this link.

By employing the MIM PV power source, the low-power MRRs, and optimizing the power management and distribution (PMAD) and MRR drive circuitry, the size of the system has been reduced by about a factor of 4 while the data rate has been increased by a factor of 40 and the power reduced by a factor of 10. A photograph of the redesigned system is shown in Fig. 15. The newly developed MIMs (Fig. 10) were not yet available for this demonstration, so 1- $\times$ 1-cm$^2$ GaAs-based MRRs developed for the Starshine project[6] were used. The MRR in the circuit is a low-power, 1550-nm device operated at 3.8 V. The electri-

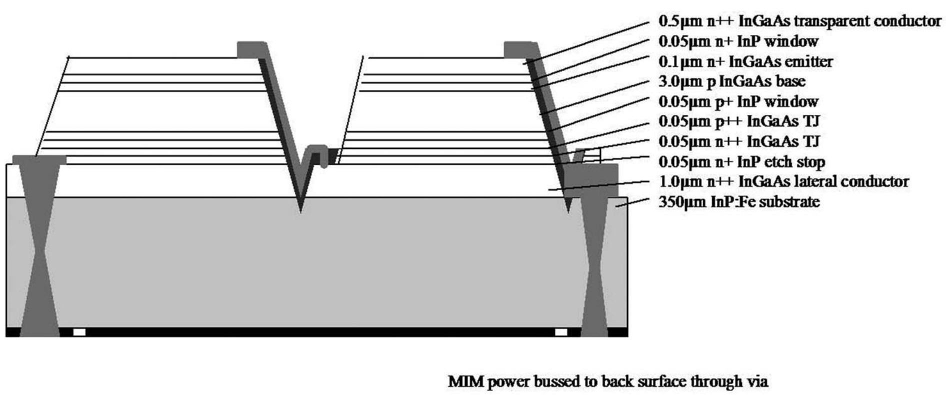


**Fig. 10** Schematic diagram of the MIM PV device.

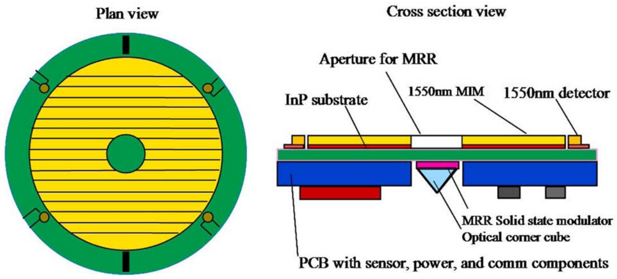


**Fig. 11** Schematic diagram of the Power-Puck structure.

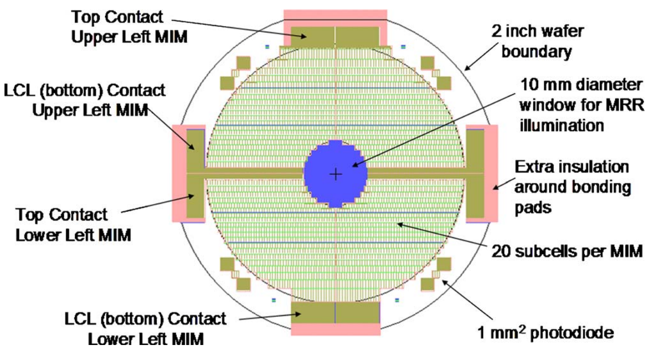


**Fig. 12** Schematic diagram of the MIM structure design for the Power-Puck.

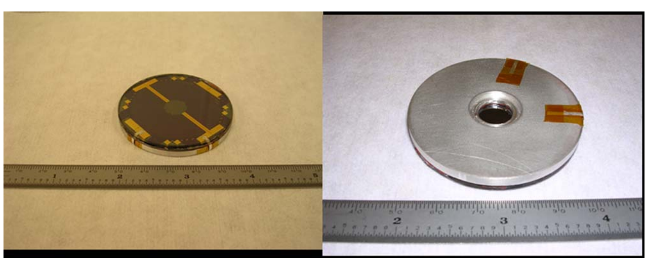

**Fig. 13** Photographs of a prototype Power-Puck: left, the illuminated side showing a processed InP wafer; right, the nonilluminated side, showing the MRR aperture.

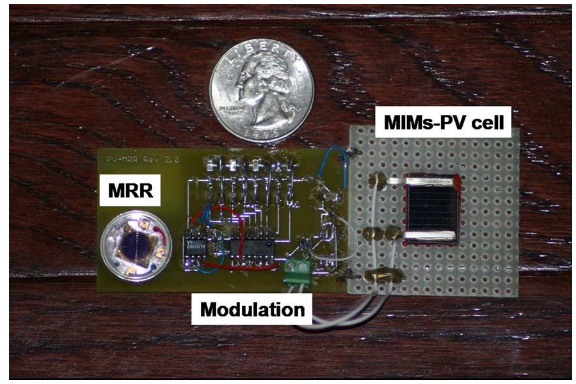


**Fig. 15** Photograph of the MIM PV power MRR data link system.

cal schematic for the system is shown in Fig. 16. The system transfers an 8-bit identification number (ID-Tag).

The system was operated in a direct-drive configuration with the MIM providing power directly to the system, and a data rate of 100 kHz at ~5 mW was achieved. The system can be operated in a capacitive storage mode where a supercapacitor (e.g., 2 F, 0.5 V) is used for energy storage. With a supercapacitor inserted into the system, continuous operation in the dark for ~30 min can be achieved following about 4 min of charging time.

This experiment demonstrated the transfer of a prestored piece of data over the PV-powered MRR. The goal of the project is to create an autonomous sensor node. With the optimized MIM inserted into this circuit, the available power will increase to ~50 mW. This translates into ~45 mW of available power for an onboard sensor. This is considerably more power than required by a temperature sensor. Indeed, the system is now being adapted to accept a low-power camera so that a low-duty-cycle video surveillance system can be fielded. The range of the system is defined by the MRR link, and real-time video links have been achieved at ranges as long as 2 km.

## 5 Summary

The development of a photovoltaically powered optical data link was presented. By integrating an advanced MIM-based PV power source with a miniature, low-power MRR optical data link, a completely self-powered, 4- $\times$4-cm$^2$ system was fielded that transmits data at 100 kHz with only

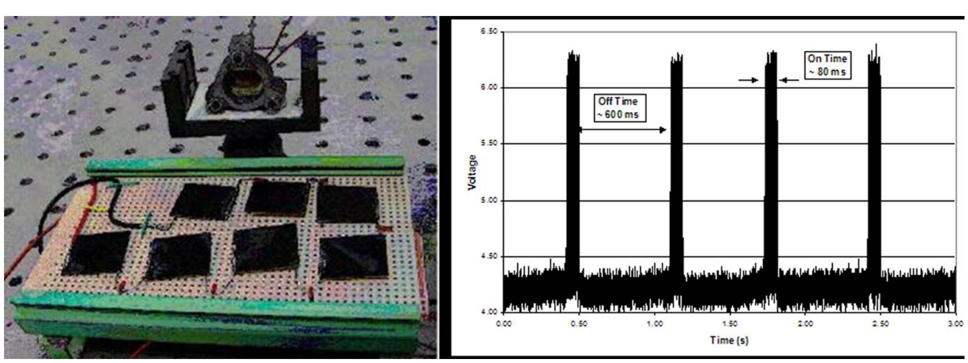


**Fig. 14** Photograph of a GaAs-based, 980-nm MRR powered by a GaAs/Ge solar array with an example of the data transferred via the link.

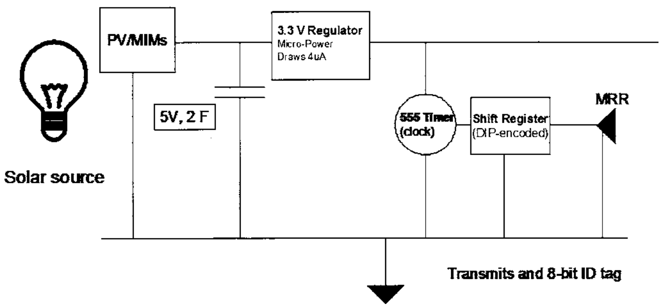


**Fig. 16** Electrical schematic for the PV-powered MRR system of Fig. 15.

5 mW of power draw. System improvements have been identified that will enable video data to be transferred with this system over ranges as long as 2 km.

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## References

1. G. C. Gilbreath, S. R. Bowman, W. S. Rabinovich, C. H. Merk, and H. E. Senasack, "Modulating retroreflector using multiple quantum well technology," U.S. Patent No. 6,154,299 (Nov. 2000).
2. G. C. Gilbreath, T. J. Meehan, R. J. Walters, S. Mozersky, M. Ferraro, S. R. Messenger, and W. S. Rabinovich, "Multiple quantum well retromodulators for low power, covert infrared data links," in *Proc. Assoc. Unmanned Vehicles Soc. Int.* Baltimore, MD (2001).
3. D. A. B. Miller, D. S. Chemla, T. C. Damen, A. C. Gossard, W. Wiegmann, T. H. Wood, and C. A. Burrus, *Phys. Rev. B* **32**, 1043 (1985).
4. C. S. Murray and D. M. Wilt, "Monolithic interconnected module with a tunnel junction for enhanced electrical and optical performance," U.S. Patent No. 6,162,987 (Dec. 19, 2000).
5. N. S. Fatemi, D. M. Wilt, P. P. Jenkins, V. G. Weizer, R. W. Hoffman, Jr., C. S. Murray, D. Scheiman, D. Brinker, and D. Wiley, "InGaAs monolithic interconnected modules (MIMs)," in *Proc. 26th IEEE Photovoltaic Specialist Conf.*, p. 799 (1997).
6. R. P. Raffaelle, P. Jenkins, D. Scheiman, M. A. Smith, D. Wilt, T. Kerslake, and A. F. Hepp, "Microsat power supplies," in *Proc. 40th AIAA Aerospace Sciences Meeting & Exhibit* Reno, NV (2002).

Biographies and photographs of authors not available.